Chapter 8

Summary and Conclusions

"The illiterate of the 21st century will not be those,
who cannot read and write;
but those, who cannot learn, unlearn and relearn."
- Alvin Toffler

"Good judgement is the result of experience,
Experience is the result of bad judgement."
- Fred Brooks

In this final chapter of the thesis, we summarize the results obtained and discuss some interesting likely future directions for our work.

MRT survey and Observations :

Imaging the southern sky at metre wavelengths with Mauritius Radio Telescope (MRT) was motivated by the existing lacuna of surveys at low frequencies despite immense scientific potential. We described the importance of low frequency surveys in radio astronomy, lack of such surveys, a revival of interest in them and the scientific motivation behind the MRT survey including its salient features. MRT is a Fourier synthesis, non-coplanar, T-shaped array with an East-West (EW) arm of length 2048 m having 1024 fixed helices and a South arm of length 880 m consisting of a rail line on which 16 movable trolleys each with four helical antennas are placed. It measures Fourier components of the brightness distribution of the sky in 63 different configurations (allocations) of the trolleys in the North-South (NS) arm over a period of time in order to sample all the baselines in the NS every 1 m. The visibilities are measured with different delay settings (up to four) to minimize the effect of bandwidth decorrelation. During the period from May, 1994 to March, 1999 more than 20,000 hours of astronomical observations (before the start of this thesis work) were carried out for the survey. The data was recorded in compressed form in chronological order of observations on about 160 data cartridges (Exabyte make) of native capacity 5 GB each. We described the observations available and the resulting dataset.

Data organization :

The most time consuming process during imaging was retrieval of data for any given sidereal hour range, spread across several data cartridges. To reduce this overhead, the entire dataset was made available online on networked hard drives accessible from computers used for processing. Each data file was subjected to data integrity checks for correct memory, header information, sidereal time stamps using software developed specifically to identify corrupt data. About 4% of data files were found to be corrupted. Corrupted and duplicate data files were removed from the database. This integrity checked database comprising of about 80,000 visibility files available on networked hard drives, facilitated immediate data access and helped in streamlining the data processing. A 3-tier archive based on Mammoth-2 data cartridges (native capacity 60 GB each), DDS-3 data cartridges (native capacity 12 GB each) and on Hard-drives (capacity 250 GB each) have been maintained for any inadvertent exigencies.

Data analysis software system :

Many aspects of imaging with the MRT are very special due to its non-coplanarity and the large size of database of visibilities (1 TB). In view of this, the imaging has been accomplished using the software system developed in-house. Additions, to provide many new functionalities and various improvements (eXtended-MARMOSAT), to the existing software system (MARMOSAT[1]) were carried out to make it complete and robust. This required optimizing, modifying/tailoring the conventional techniques for data processing, making the right choice of methods to analyse, browse and display large amounts of data obtained at different stages of imaging. An hierarchical software system based on a mix of top-down and bottom-up approaches consisting of separate application programs with specific functionalities (top-most layer) and using general purpose generic libraries (lowest layer) was developed to accomplish this purpose. We described the basic guidelines followed during its design. The application programs are executed one after another in a sequential manner and communicate via standard data files. The data analysis software system comprises of more than 60,000 lines of code in a variety of languages, namely: *C, Perl, Matlab* and *F77* and in addition uses shell scripts extensively. The goal has been to take the advantage of natural strengths of each programming language to optimize the software development efforts. Its organization is modular so that additions and modifications can be easily carried out.

Automatic evaluation of data quality:

A novel framework to automatically evaluate the quality of visibility data depending on its suitability for imaging was developed. This was essential to classify the ≈20,000 hours of astronomical observations for the survey. The framework is based on the assumption that the suitability of a data file for imaging is a function of four key parameters namely, its completeness, interference statistics, rms noise and effect of Sun and in addition the quality of its calibration file. To a visibility file, for each key parameter, a numerical index from 1 to 9 called the Quality Factor (QF) is assigned which assesses the extent up to which the observed visibilities satisfy the expected requirements for that parameter. A lower value of QF indicates a better quality data. QF of 1 indicates data of best quality while QF of 9 indicates data of a very poor quality. Generally we consider a QF less than 5 as acceptable. The overall quality of a visibility file is calculated using the four QFs assigned. Thresholding is applied to avoid files which rank poorly in certain QFs, but are within acceptable quality limits based on other QFs. The algorithm for the data quality evaluation process is implemented in the form of a stand-alone computer program written in *Perl.* This accomplishes data classification automatically without any manual intervention.

We compared our results of automatic classification with that of the traditional manual approach based on human expertise using two schemes on a total of about 600 visibility files. In the first scheme each data file was classified in three categories namely: good data - acceptable for imaging, poor data - which is doubtful and bad data - to be rejected.

[1]**MAuR**itius **M**inimum **O**perating **S**ystem for **A**rray **T**elescopes.

The comparison between the human and automatic classification agrees in about 87% of the cases. In the second scheme the data files were ranked in relative order of quality. On an average within a difference in the relative ranks of ±1 the agreement is 80%. The agreement increases to 92% when the difference of the relative ranks is considered within ±2. A careful analysis of discrepant cases revealed that in most cases the automatic ranking was more appropriate. The comparison very clearly proves that even with a simple model the automatic classification scheme is efficient and reliable. The framework was used to automatically classify the data for the entire survey and brought down the time required for imaging from a few months to a few hours. It also gives a comprehensive overview of the quality of the entire survey data.

To our knowledge this approach is the first of its kind in radio astronomy to automatically classify astronomical data based on its quality. With suitable modifications it has the potential to be used for other data sets in astronomy. The fuzziness of the nature of the problem will always limit the viability of the data classification by any technique, as there is no unique benchmark to indicate the quality and compare the results. Nevertheless the results and its agreement with the traditional approach to a good extent should motivate us to improvise it and implement it for data sets of other synthesis telescopes. The future belongs to array type telescopes involving large number of baselines, number of frequency channels etc. and an astronomical tool based on such an approach may prove handy and also play a role in monitoring the performance of an observatory itself.

Hierarchical RFI mitigation system :

RFI poses a serious problem at MRT due to its low frequency of operation and wide primary beam (EW×NS $\approx 2^\circ \times 60^\circ$). We use XF correlators, where we cannot reject parts of the observing band in which the interference occurs and use the rest of the band. In addition to this, the large volume of data necessitated the need for a robust automatic RFI detection scheme. An hierarchical scheme was developed with a view to achieve an effective, reliable and non-toxic automatic RFI mitigation at MRT with minimum possible human intervention. It uses a conjunction of signal processing techniques both linear and nonlinear. These include Thresholding, Fourier filtering, Hampel filtering, Model fitting, Decision based algorithms and Visual inspection. We have also exploited the information that the sky signal is correlated day to day but interference is most likely not.

In synthesis imaging, a sharp feature in the visibility domain transforms to a sinusoid in the image domain and vice versa. So for best interference detection it is desirable to exploit both the domains. At MRT, interference detection is carried out at various steps of data processing, namely : sum of magnitudes of visibilities on all the baselines, self correlation measurements, each day's image before post-integration and finally by using all the one day images collectively for interference detection. The original data is not modified and the complete information about interference is stored in an updated centralized flag table from which it is retrieved as and when required. Interference excision is carried out at two stages (apart from excision in self correlation measurements), firstly at the level of each day's image by giving zero weights to the data points affected by interference (detected up to the stage of each day's image before post-integration) during post-integration. In the second stage the interference which is detected using all the one day images collectively, is excised during their co-addition to obtain the full resolution images. During co-addition, the 1-D image scans along declinations at the sidereal times affected by interference in the individual one day images are estimated by interpolating the adjacent 1-D image scans free from interference.

The principles and techniques used in the development of the RFI mitigation system are of very general nature. We believe that such an approach based on a conjunction of linear and nonlinear techniques exploiting their natural strengths and judiciously applying them at various stages of data processing is an important step in the interesting future direction of research to accomplish the ultimate goal of achieving completely automatic data flagging.

RFI Statistics:

Use of an RFI database is valuable to investigate the nature of interference at an observatory site and develop appropriate techniques for its mitigation. In this context, we presented the interesting aspects related to interference statistics arising from our studies based on the ≈20,000 hours of astronomical observations. The statistics revealed that ≈10% of the our data is affected by interference. The total data affected (≈15%) during the day time (from 6 a.m.-6 p.m.) is three times compared with that (≈5%) in the night (6 p.m.-6 a.m.). This confirms the general belief that the night time observations are relatively interference free. The number of interference points above a strength N(>S), can be modeled as a sum of two exponentials, N(>S)=A exp(-B/C)+D exp(-S/D), where S is strength of interference in units of rms noise. At this stage we are unable to associate physical processes likely to be responsible for such a behavior.

The number of interference points is highest in the strength bin around 10σ, during both day and night. There are 90% of the interference points having strength less than 580σ in the total data. The interference is generally having higher strength in the day time compared to the nights.

In the total data, about 45% of the interference bursts last for less than one integration period (≈1.1 s) while it is 41% and 56% during the day and the night. About 88% of the interference bursts last for less than 4 integration periods in the total data. It revealed that the interference is generally short lived and justifies our approach, that most of the interference excision can be carried out at the level of each day's image by giving zero weights to the points affected by interference during post-integration.

There is a marked increase in interference during working hours of the local industry (MST 8-16 hrs) which accounts for $\approx$ 62% of the total interference in the entire sidereal day. This increase indicates that the increased interference during the day is perhaps linked to the local industry if effect of solar interference is not the sole cause behind it. We need to compare the interference on public holidays in order to distinguish between the two.

The number of interference points detected in the visibilities is $\approx$9.7% as compared to $\approx$0.3 % in the images. It showed that there are very few interference points which escaped the automatic interference excision in the visibilities. More than 99.7% of the interference is detected automatically, the remaining is detected by semi-automatic methods. The images obtained after applying the RFI mitigation system are free from any perceivable interference and demonstrate its effectiveness.

Correcting time stamping errors :

The sidereal time stamped in the visibility files has an uncertainty of 1 s. A simple procedure based on the fact, that the time resolution information from the astronomical clock at MRT is accurate down to 1 millisecond and the integration time of visibilities is known to an accuracy of much better than 1μs, was developed to correct the time stamping errors after taking into account data slips and glitches. Using the procedure developed, the sidereal times of the visibilities were estimated to an accuracy close to a millisecond.

Post-Integration of self correlation measurements :

At MRT we use 64 self correlation measurements (32 EW, 16 NS cosine, 16 NS sine) to estimate the normalized correlation coefficient from the measured digital correlation counts. Due to broad primary beam of both the EW (2° i.e. 480 s) and the NS (15° i.e. 3600 s) groups in RA, the rate of change of self correlation measurements is a slow function of time. Taking advantage of this, their integration time was increased from $\approx$1.1 s to $\approx$67 s to increase their signal to noise ratio. The time for averaging the self correlation values was decided after carefully examining the actual data and carrying out interference excision.

Calibration :

The calibration of visibilities at MRT was accomplished by using observations of well known strong point sources in the sky. Due to confusing sources in the broad primary beam and lack of suitable calibrators in the southern sky, on any given day we could calibrate our array using only three sources MRC0915-118, MRC1932-464 and MRC2211-172.

The effect of other sources is minimized by carrying out a least square fit of the expected visibilities to the measured visibilities. For baselines with short EW components the effect of other sources apart from the phase calibrator can be significant. To estimate the complex gain of short baselines, we used closure information obtained with the last EW group (E16). Once the baseline based complex gains were estimated, the antennae based solutions for amplitudes and phases were determined. Since the number of baselines are 512 while there are only 48 independent complex antennae gains, this improved the accuracy of estimation of complex gains significantly. Since this is an over determined system, baselines with short EW components were not used. The complex gains obtained using the delay zone in which the phase calibrator is present were used to estimate the complex gains for the other delay zones. In order to accomplish this we use the information about the receiver configuration, the centroids of the bandpasses of each baseline. The variation in the centroids of the bandpasses cause only a 5° rms error in the instrumental phase calibration.

We estimated the amplitude and phase stability of the array. We find that the day to day rms variation of amplitude and phase per baseline estimated using the same calibrators is within the range 5% to 10% and 5° to 10°, respectively. The rms phase variation per baseline when estimated using different calibrators (at different declinations) on the same day is in the range of 10° to 15°. The final image is synthesized by using $\approx 32\times 880$ baselines. The expected dynamic range limitation due to a phase variation of 15° is of the order of $15\times\frac{\pi}{180}\times\frac{1}{\sqrt{32\times 880}}\approx\frac{1}{640}$. This is quite acceptable and in fact we are dynamic range limited by other factors like rms noise and accuracy in the estimation of the PSF.

Wide field imaging :

The FWHM of the primary beam response of an EW group is 2° (HA= $\pm 1^\circ$) which limits us to image this region of the sky at any given time. The sampling of the visibilities in the EW direction is at intervals of 64 m which is also the size of an EW group. Due to this, when the beam is synthesized on the meridian, the grating responses fall at the null points of the primary beam response of the EW group but when the beam is synthesized away from the meridian, the grating responses fall within the primary beam of the EW group. The synthesized beam (including the aliasing) varies with the hour-angle at which it is synthesized. As a result, the dirty images will have a complicated appearance which would be difficult to analyse and interpret. The deconvolution of such images would be prohibitively complex. Due to this, imaging for the survey is carried out only on the meridian. The scanning in right ascension is provided by the motion of the Earth and the 2-D image is formed by stacking the 1-D images on the meridian for the observable range in declination at different sidereal times.

A simulation study carried out earlier revealed that even if we use six tangent planes to cover the entire declination range for inversion of visibilities to brightness distribution the loss in amplitude and position errors introduced due to the effects of non-coplanarity are not acceptable. In view of this, we image by rephasing the calibrated visibilities for all the baselines at each point in the sky at transit and combine them to obtain the dirty image at that point. The heights of the groups and their distances as measured are used. This method of direct phasing is expensive in terms of computation but there is no assumption either about the regular sampling of the visibilities or about any slope of the track along the NS. But this method of inversion of visibilities to the brightness distribution requires Direct Fourier Transform (DFT) and thus prohibitively slow, which was crucial obstacle for obtaining wide field imaging for the survey in a short time. To accelerate the imaging process, optimization based on look-up table approach was adopted which resulted in a significant decrease in the time required for the inversion by a factor of about ten. The time for imaging one sidereal hour range across the entire declination range for any allocation was reduced from ≈50 min to ≈5 min (on a Intel-2.4 GHz, P4 processor).
Imaging guard zones along RA : The dirty images were synthesized on a sidereal hour basis for each allocation. Since the observations have been carried out for nearly five years the actual region of overlap (in any common epoch) for which the full resolution image can be obtained by co-adding all the one day images, is less than one full sidereal hour range (due to different amount of precession for each day's image). In addition, we need images of adjoining regions on both the sides in RA as guard zones to successfully deconvolve the dirty image near the boundaries of the sidereal hour range under consideration. In view of this, for each day's image, the visibilities corresponding to the sidereal hours on both the sides (observation stretch on the same day) were also imaged separately and later joined along RA to obtain an image covering nearly three sidereal hours in RA corresponding to each day.

Separate images for each day's observation and each delay zone were made. Data for different days were not combined and imaged, so as to take into account the different precession of different days separately. In fact having images on different days separately provides an additional checkpoint in the processing stages and gives the flexibility of rejecting or accepting any visibility. Each day's image is individually passed through the RFI detection checks to sieve maximum possible remaining interference at this stage before any box-car averaging so that we lose visibilities corresponding to only ≈1.09 s as compared to 4 s after post-integration.

Box-car averaging, precession and regridding :

Each day's image was box-car averaged for 4 s. At this stage any RFI detected at all earlier stages were excised by giving zero weights to the points corrupted by interference. Each day's image was precessed to the epoch J2000 on a common uniform grid which has 900 points in one sidereal hour range and 4096 points in the entire $\sin(za)$ range of ±1, which translates to $\approx$2,300 points for the declination range of interest to MRT. There is a danger of precessing the dirty images as the sidelobes of a source get precessed differently compared to its main beam. Fortunately the effect of this differential precession is not significant. Its maximum value is only about 0.3% and thus ignored.

Each day's image analysis :

After obtaining different day images, which are on the same grid in the epoch J2000, each image was analysed collectively to detect any remaining RFI. The images were also affected by artifacts such as residual DC mostly due to correlator offsets. Careful analysis revealed that the DC at the level of each day's image, varies with declination but is almost constant in time. Images which showed DC varying with time, or with suspicious features were summarily rejected. We decided to let the residual DC pass through at the level of each day's image and filter it out in full resolution dirty images itself.

Two dimensional fitting was carried out in each day's image for at least two well known unresolved bright sources selected from the MRC catalogue at 408 MHz, to confirm their detection at the expected positions and images with poor fits were rejected. Their positions were also examined from day to day to check for any positional shifts beyond the expected FWHM of the beam due to any ionospheric effects or improper calibration.

The rms noise measured in each day's image, was compared with the images of nearby allocations. Images with relatively high rms noise (by a factor of 2.5 when compared to each other) were rejected. At MRT we are also affected by a number of unidentified satellites, which appear as transient sources in the images. Each day's image was visually inspected in grey scale and also using contour maps to look for such possible candidates. The real and the imaginary parts were also examined to check for calibration, by ensuring that the imaginary part is zero near the transit of a strong unresolved source. Only images which satisfied all the acceptable criteria were considered for co-addition to obtain the full resolution image.

Full resolution dirty images :

To keep the average bandwidth decorrelation to a minimum, the four sets of images (corresponding to four delay zones) were obtained by combining images of allocations in block-1 and block-2 with images corresponding to appropriate delay zones of allocations in block-3 to block-10. The delay zones were chosen appropriately for each block with the aim of minimizing the resultant bandwidth decorrelation across the declination range of interest in the full resolution images. All the interference detected during the combined data set of all the one day images, was excised during co-addition in each day's image and the 1-D image scan along declination at the sidereal time affected by interference is obtained by interpolating the adjacent 1-D scans which are free of interference.

First all individual images of the same allocation are combined with natural weights (square of the signal to noise ratio, after equating the deflections obtained on the same source) and one resultant image with the maximum possible signal to noise ratio is obtained for each allocation. The resulting images obtained for each allocation were combined (across different allocations) with weights equal to inverse of deflection to obtain the full resolution dirty image. This hybrid approach achieves the best possible sensitivity with the constraints of obtaining dirty beam closest to a *sinc* function. Since the *uv* coverage is nearly complete and uniform, the PSF is essentially of a filled cross. The weights used while co-adding images for all the four delay zones are derived via fitting for the images of the delay zone in which the strongest unresolved source is present and applied to the images of all the delay zones. For each sidereal hour range, four sets of full resolution dirty images are produced separately to cover the entire declination range of MRT.

The full resolution dirty images were analysed for rms noise, positional accuracies and spurious artifacts. The dirty images were also affected by spurious features which have non-astronomical origin. These include residual DC whose strength is constant in RA but varies in declination. They appear in the contour image as horizontal ridge lines parallel to RA axis of constant strength but vary with declination. The residual DC was estimated at each declination by averaging the intensity of all the pixels in empty regions which have strength less than thrice the rms. The empty regions were manually marked after visual inspection of the images itself. The effect of rms noise and astronomical signal gets heavily suppressed during averaging and an accurate estimate of the residual DC is thus possible, which is then subtracted from the original image. The DC remaining in the images is always less than 20% of the rms noise. The grey scale and contour images were inspected to confirm that DC removal does not lead to loss of any significant astronomical information from the images.

The other spurious features include aliased images or sources appearing in grating lobes. These do remain in the image and cannot be further reduced. They arise due to a few missing allocations and due to the bandwidth decorrelation being different at same declination in different allocation images which changes the effective weighting with declination. The sources which cause maximum corruption in the images are Cygnus A and Cassiopea A.

Deconvolution of wide field images :

Due to non-coplanarity, the Point Spread Function (PSF) becomes declination dependent. This difficulty is further compounded by the declination dependence of the bandwidth decorrelation and natural stretching of the FWHM of the beam in RA by $\sec(\delta)$. For MRT the effects of differential precession of the sidelobes as compared with the main beam and interference on the PSF were investigated and found to be insignificant. For deconvolving the wide field images ($40°\times35°$) at MRT of a given delay zone, we generate PSFs (extent $\approx 9°\times15°$) at specifically chosen declinations such that the maximum error by approximating the PSF at any declination, with the closest available PSF is <0.2%. During deconvolution (using Högbom CLEAN), the algorithm approximates the PSF at the current detected peak position by the closest available PSF. This avoids the need for PSF interpolation in the image plane which significantly accelerates the deconvolution process. Additionally, the positions of bright sources having flux densities above a threshold limit are estimated from the raw images and PSFs of larger size (extent $\approx 18°\times15°$) are generated at those declinations.

Generating full resolution PSFs at all the required declinations for an image covering one sidereal hour image and all the four delay zones is computationally expensive and would have taken ≈12 days on a 2.4 GHz processor, which would make the approach impractical. For this purpose a master data bank of PSFs at all the declinations for each of the allocations was generated and stored on the hard-drive. Estimation of the PSF for the full resolution image for any sidereal hour and a given delay zone, is obtained by retrieving these pre-generated PSFs of different allocations which are then combined with appropriate weights to incorporate the effects of weighting and bandwidth decorrelation. This drastically brought down the time required by a factor of ≈150 and the full resolution PSFs for the entire declination range (all the four delay zones) corresponding to one sidereal hour range can be generated in ≈2 hours. The generated PSFs are stored as a data bank on the hard drive.

The deconvolution program is equipped with a Graphical User Interface which has provision for masking regions effected by artifacts. These forbidden regions are not considered for searching the peaks during the CLEAN. The images have been CLEANed down to 5σ level with a loop gain of 0.05 and generally the number of iterations needed is in the range 15,000-25,000. A two dimensional elliptical Gaussian having width equal to the expected resolution corresponding to the maximum baselines (up to which the measured visibilities have been used) was used as restoring beam. The restoring beam was appropriately rescaled to have an area equal to the area of normalized dirty beam at each declination to ensure flux conservation while convolving the clean components. Due to the uniform *uv* coverage generally the process of CLEAN is trouble free. The achieved dynamic range is approximately 70. Since the PSF is that of a cross, the dynamic range is higher along the diagonals. The deconvolved images were inspected to confirm that there were no undesirable effects produced during deconvolution.

Scaling images to a common level :

Since the full resolution images for each sidereal hour were obtained by co-adding one day images using relative weights determined by fitting different strong unresolved sources they are in arbitrary flux density units and not in a common scale at this stage. All the point sources with peak flux densities more than 10σ in each sidereal hour image were detected and nonlinear fitting was carried out using a two dimensional elliptical Gaussian beam for estimating their peak flux densities and the positions[2]. The ratios of the fitted peak amplitudes of common unresolved sources in the overlapping regions of two adjacent images was used to scale them from arbitrary units to a common level. The analysis revealed that the rms scatter of the peak flux density ratio of common sources between images of two adjacent hours is within ≈5%. This gives a rough upper estimate of the internal flux density accuracy of the images due to the combined effect of independent data used and various steps involved during the synthesis of images. Subsequently we used the method of differences to scale all the images to a common reference.

In order to minimize the error due to scaling the image covering the sidereal hour range 21-22 hrs was considered as the reference image as it is approximately in the center of the RA range of the images presented in this thesis. This image also happens to have the minimum rms noise. The maximum error due to scaling the deconvolved images is ≈0.9% while for the dirty images it is 1.35% (due to the maximum distance from the reference image). The difference in positions of the common sources in the overlapping regions is within $\approx 0\farcm16$.

Estimation of the primary beam shape of the helix :

We have estimated the primary beam shape of the helix using the ratio of the fitted peak flux densities of unresolved sources in our images at 151.5 MHz to their peak flux densities at 408 MHz (from MRC). To ensure that the estimation is unbiased due to the width of spectral index distribution, a large (about 580 sources) but flux density limited($>$ 1.25 Jy at 408 MHz) complete sample of MRC sources, all of which (96.5%) were also detected in our images, were considered. The estimated primary beam using different data sets agree with each other within 3%. The estimated primary beam is broader having a FWHM $\approx 64^\circ$as compared to $\approx 56^\circ$ of the expected beam. It also has a maximum response at a declination of about $-44\fdg02$ instead of expected declination of $-40\fdg14$. The estimated beam was used for primary beam correction in subsequent analysis.

[2]For dirty images which were not deconvolved a 2-D sinc function of the expected FWHM was used to carry out the fit.

Estimation of the unnormalized correlation coefficient :

In the 2-bit 3-level correlator at MRT, AGCs maintain a constant signal level to the samplers even though the background temperature of the sky changes. This leads to similar correlation for strong sources in a strong background and weak sources in a correspondingly weaker background. In order to measure the absolute variation of the background radiation as seen by one of EW and one of NS groups, the self correlations were measured without the AGC. Continuous stretch of observations of self correlation without AGC, on a number of days when Sun is in northern sky and at least 4 hours away from the meridian for the entire stretch of observations were examined from the database. These were subjected to threshold checks, checks for level jumps, self consistency with each other and the expected response, followed by robust Hampel filtering to remove any interference. The estimated total powers along RA from each day measurements were convolved with the beams of the EW and the NS groups. The total powers on all the days at each RA were averaged to get a mean value of the powers measured. The power as seen by any EW×NS interferometer was calculated using the relation $P_{ew\times ns} = \sqrt{P_{ew}P_{ns}}$.

This estimated background variation using the non AGC self correlation measurements contains the shape and has to be appropriately scaled before it can be applied on the images to incorporate the background variation. This scaling is required for two reasons, firstly the measurements can be affected by a gain factor and a constant level shift and secondly the images are in arbitrary units. To get the required scaling, the ratio of flux densities of 55 MS4 sources with their fitted peak flux densities in the MRT images (after the images have been scaled to a common scale and helix primary beam correction is applied) was plotted as a function of RA. This ratio was fitted as a linear function of the total power estimated using the self correlation measurements without the AGC. This gives the correction factor required to incorporate the variation in the background temperature of the sky and transform the images from arbitrary units to true flux densities.

Primary flux calibrator :

After incorporating the variation in the background temperature of the sky by the method described above, the images were also transformed to true flux density scale. However, it is customary to refer to the true flux densities of surveys based on a few well known calibrators. In order to choose a primary flux calibrator with reference to which all the flux densities at MRT would be referred, we looked for sources which are strong, unresolved, non-variable and whose flux densities are accurately known at a large number of frequencies including those near 151.5 MHz. After going through several possible sources we chose MRC2354-350 having a flux density of 26.30 Jy at 151.5 MHz as the primary flux calibrator. The flux density has been estimated by fitting the measured flux densities based on the measurements available at different frequencies. The peak flux density of the calibrator in the image is $\approx$95σ (σ $\approx$265 mJy beam^{-1}). All the flux densities in the MRT images were rescaled (up by about 0.78%) accordingly to keep in accordance with the quoted flux density of the MRC2354-350.

Wide field images :

As one of the main thrusts of this thesis, we presented deconvolved images with a resolution $4'\times4'.6\sec(\delta+20^{\circ}.14)$ in J2000 coordinates covering more than one steradian of the sky ($18^h \leq$RA$\leq 24^h 30^m$, -75°$\leq \delta \leq$-10°). The full resolution dirty images with the same resolution covering an additional, about half a steradian of the sky ($15^h 06^m \leq$RA$\leq 18^h$, -75°$\leq \delta \leq$-10°) which includes a large part of the southern Galactic plane including the Galactic center were also presented. As a result of imaging guard zone on either side in RA and declination and later scaling all images to a uniform level using the method of differences described earlier, there are no discontinuities at the end of each sidereal hour and at the end of each delay zone.

For each one sidereal hour range, the full declination range is covered by a part of four images which have been made by combining images corresponding to different delay zones. These parts are so chosen that the average decorrelation at any declination is minimum and always less than 18%. Due to bandwidth decorrelation, the peak amplitude of sources is affected at the expense of resolution to conserve the flux. In the deconvolved images the peak amplitudes have been restored to the appropriate value but the signal to noise ratio remains reduced. The FWHM of the beam in RA varies from 16.25 s (at δ=-10°) to 61.82 s (δ=-75°) by a factor of $\approx$3.8. The FWHM along declination is constant in $\sin(za)$ coordinate system but varies as a function of declination in angular extent from $4'.6$ (δ=-20°.14) to 8′ (δ=-75°) by a factor of $\approx$1.7.

uv coverage : At the level of one allocation's image all the 480 baselines are used as no baselines are rejected while imaging. Thus the *uv* coverage of the images presented depends upon the availability of images for different allocations which have been used to obtain the full resolution image. For most of the images presented in this thesis, the *uv* coverage is nearly complete and uniform. The number of allocations present to obtain the full resolution images vary between 47 to 54 out of a total 60 allocations. Most of the allocations from 1-12 which contain short spacings are also present in all the images. Due to good *uv* coverage the MRT images are sensitive to the extended structures and their morphologies are well represented in our images.

Artifacts in images : Unavoidably certain regions of the map have been affected due to a variety of features which can be broadly divided into sources appearing in grating lobes/aliased images, sidelobes of strong sources which could not be deconvolved properly and regions affected by residual DC along RA which could not be effectively removed from the images. The reliability in such affected areas is best judged by the examination of the contour maps itself.

Noise in the images: The rms noise varies with RA due to changing brightness temperature of the sky and the number of days of data used, from 260 mJy beam^{-1} to 390 mJy beam^{-1}. Since the response of the helix varies along declination (due to meridian transit imaging, there is no effect of helix response along RA), the sensitivity also becomes progressively poorer in declinations away from the direction of the peak response up to a factor of two at the ends of declination range of interest.

The measured noise in the images is higher compared to the expected noise on an average by a factor of 1.7. There are various factors which may likely be the cause of the higher rms noise. Some of them are higher receiver temperature than assumed value of 400 K, aliased images, possible residual sidelobes, residual DC, calibration errors and weak interference. It is likely to be a combination of many factors which may be responsible to give this higher value of rms noise. In addition, within each allocation's image the weighting is uniform due to which the thermal noise suffers.

Surface brightness sensitivity: The expected point source sensitivity in the synthesized images in MRT changes depending upon the region of the sky under consideration due to which the corresponding surface brightness sensitivity also changes. Taking the worst case for rms noise as ≈390 mJy the surface brightness sensitivity is $\approx 2.1\times10^{-21}$ W m^{-2} Hz^{-1} Sr^{-1} (1σ at 151.5 MHz). Due to this good surface brightness sensitivity at low frequency, the images are suitable for the study of extended features.

Source catalogue: An algorithm was developed for extracting sources from the MRT images. A source catalogue of nearly 2,800 (5σ) unresolved and extended radio sources has been derived from the images was presented. Initial analysis of the catalogue and its cross comparison with the MRC Catalogue at 408 MHz and Culgoora Catalogue at 160 MHz were carried out and is on the expected lines.

Interesting sources: The maps presented in this thesis cover a large region of the sky and contain considerable amount of information. It is beyond the scope of this thesis to give a complete analysis of all this data. However a few interesting sources of the images were presented as representative of astrophysical potential of the images. A set of more than 100 steep spectrum sources (based on ≈1,700 common sources with the MRC) have been identified for further investigation. About a thousand sources detected in our images are not listed in the MRC. Most of them arise due to the incompleteness of the MRC below 1 Jy but some of them are genuinely steep spectrum. It will be interesting to look at each one of these sources to form a likely sample which can be further studied for searching high redshift galaxies. It is not known how many of these total steep spectral index sources will actually be high redshift galaxies, however even a small fraction would be important to increase the known population. A few examples of other interesting sources in the images like giant radio sources, double sources and cluster radio relics/fossil galaxies were also presented.

Due to availability of short spacings and nearly complete *uv* coverage, our images are suited to study the morphology and spectra of Galactic supernova remnants (SNRs), which are used as primary signatures for their identification and classification. With our resolution of $4' \times 4'.6 \sec(\delta + 20^\circ.14)$ and achieved surface brightness sensitivity, these objects having a typical size $11'$ and surface brightness of $\approx 1.5 \times 10^{-20}\,\mathrm{W\,m^{-2}\,Hz^{-1}\,Sr^{-1}}$ (at 151.5 MHz) are generally resolved and detectable in our images. We have been able to easily identify about 50 SNRs out of 80 known in the literature in the region imaged. A few of the extended and interesting SNRs are also presented. Our achieved surface brightness sensitivity is significantly better than the surface brightness limit up to which the SNR catalogue is believed to be complete. Thus it would be useful to look for new low surface brightness SNR candidates in the images especially the ones which are large sized and older and are believed to be missing from the known catalogues of SNRs due to selection effects.

We reported structure of a few extragalactic extended sources in the images. Comparison of the images of a few extended sources from the literature at nearby frequencies confirmed that their morphology is well represented in our images. The sample of the extended sources is a representative of the strong extragalactic radio sources in the region of the southern sky imaged, but is statistically not complete. We also presented a specific example of extended radio emission around the X-ray cluster Abell 3667 in our image along with a contour image from the ROSAT overlaid on a grey scale radio image at 843 MHz from the MOST. These reactivated fossil galaxies are powerful tools to investigate the properties of infalling matter onto the clusters of galaxies and a test ground of large scale structure formation. These are steep spectrum sources and we expect to detect quite a few such sources in the MRT survey.

Future Work : The future work is likely to proceed in three separate directions.

Imaging of the remaining regions of the sky :

Imaging of the remaining regions of the sky needs to be continued systematically. All the techniques and software required to complete the survey up to source catalogue construction have been developed and demonstrated. Since, no new work in terms of development of new algorithms and corresponding software need to be developed, the remaining work is expected to progress at a substantially faster rate.

The images of the Galactic plane presented in the Appendix A have not been deconvolved. Their deconvolution needs to be carried out. One most popular approach would be to use multi-scale CLEAN. Another approach worth considering is the one in which we search for CLEAN components based on the local maximum rather than the global maximum. The latter would be much easier to apply while for the former suitable changes to the deconvolution code would be needed.

Astrophysical interpretation and follow up :

Only a preliminary analysis of the images presented has been carried out. Their detailed analysis to exploit their full potential would be the next logical step. This includes follow up work related to the steep spectrum sources, SNRs and extended extragalactic sources. Comparison of the MRT sources with the other higher frequency catalogues like SUMSS, PMN (Parkes-MIT-NRAO) and Cross identification at other wavelengths using optical catalogues and IRAS (InfraRed Astronomical Satellite) sources needs to be carried out in the near future. Some of the studies which can be undertaken include correlation of MRT sources with galaxy clusters, nearby spiral galaxies and Radio-FIR correlation. The catalogue can be used for making complete samples which would also require followup work including high resolution observations for accurate positions followed by optical observations. Another interesting direction would be to look for low surface brightness extended features in the images for cluster relics/fossil galaxies.

Towards higher sensitivity survey :

A challenging task that lies ahead and should be followed is to obtain the final images with substantial better sensitivity and dynamic range by 2-D synthesis so that the noise in the images reach closer to the confusion limit. For this we need to image the full 2° available[3] instead of imaging only at the transit. Imaging away from the transit would require the deconvolution scheme to take into account the variation of the synthesized beam with hour angle. If this can be achieved it would make MRT equivalent of 74 MHz VLA Low frequency Sky Survey (VLSS) in the southern sky in terms of rms noise in the images. This in turn needs the calibration process to be substantially improved.

The calibration process is particularly limited by the calibration scheme used so far. We need to improve on the present technique to improve the dynamic range of the images. Instead of using a single source calibration we need to do either a 'field of view' calibration which would take into consideration contribution of several sources in the field of view or use redundant baseline calibration.

In the third cycle of observations we have also acquired data in (E+W) $\times$ E and (NS+W)$\times$NS mode to enable us to carry out redundant baseline calibration. Using this

[3]The FWHM of the beam of an east-west group.

data could improve our calibration process which would be independent of the knowledge of source structure and position. However, the limitations due to the baselines not being entirely redundant because of height variations and due to variation in bandshapes need to be considered for understanding the limitations of this technique at the MRT. Unequal bandshapes also limit the use of closure phase in calibration and in deriving antenna based gains from baseline based gains. A limitation is that we would not be able to calibrate the data recorded in the first two cycles of observations with this technique, which makes this technique less attractive for MRT.

Field of view calibration can be taken up in two ways. In the first one since the flux density and positions of sources are not known at this frequency, there is a need to produce an initial image with the final resolution and make estimates of the position and flux densities of the sources and use them in the calibration process. The images presented here can be used as a base for first iteration for this purpose. The process may require a few iterations of calibration and imaging. The second approach perhaps simpler, would be to use the SUMSS catalogue as the model and phase calibrate the array on similar lines as the field of view calibration scheme followed for VLA 74 MHz VLSS survey.